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A CENTRIFUGAL HYPERSONIC WIND TUNNEL FACILITY FOR INVESTIGATING EFFECTS OF INERTIA
ON ABLATING BODIES—JOSEPH S. FORD II

A CENTRIFUGAL HYPERSONIC WIND TUNNEL

FACILITY FOR INVESTIGATING EFFECTS OF INERTIA

ON ABLATING BODIES

A THESIS

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Dean of the Graduate Division

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I. INTRODUCTION

A most important aspect of space technology is the development of methods for atmospheric re-entry. In this phase of flight very severe structural and material requirements exist. The origin of the problem lies in the intense aerodynamic heating which occurs as the body enters the denser regions of the atmosphere. High stagnation temperatures at the nose, shear effects in the boundary layer, radiation from the hot gas in the shock wave, and heat liberated by the recombination of dissociated and ionized gases give rise to conditions which will result in the destruction of the body unless some form of heat protection is provided.

At the present time ablating materials have proved to be the most successful form of protection for re-entering bodies. As there are few substances which sublime directly, materials which soften and have highly viscous phases are sought. It can be demonstrated that the effects of inertial forces on a viscous ablating layer are as significant as the effects of shear forces. Thus the process of ablation must be as dependent upon the deceleration of the body as upon the flow conditions.

In present experimental studies only the flow conditions are simulated. It is the purpose of this thesis to report an investigation into the feasibility of a facility in which both flow and inertial effects can be examined. Our studies indicate that, within the present state of the art, it is practical to combine an electric arc driven hypersonic wind tunnel and a centrifuge into a system in which this closer approximation to the environment of re-entry can be achieved.

II. A RE-EVALUATION OF THE PROBLEM OF RE-ENTRY SIMULATION

Versatile facilities for the simulation of re-entry are a vital link in the design and development chain for orbital vehicles. A ground complex in which various aspects of a problem can be dealt with individually or in combination can provide a better insight into the basic mechanism of a process than can otherwise be obtained. Furthermore, in such a facility, instrumentation, controlability, and repeatability of conditions are difficulties of lower magnitude than those experienced in live tests. These remarks appear particularly pertinent to the investigations of ablation as will be demonstrated in the succeeding paragraphs of this section.

Precise definition of the kinematics of re-entry proved extremely difficult. Fortunately in 1952, Allen and Eggers [1]* at the Ames Research Center made a drastic simplification which gave realistic data for ballistic trajectories. This simplification resulted from the realization that the variation in atmospheric density can be closely approximated by an exponential function of the form $\rho = \rho_0 e^{h/H}$, the drag coefficient for a given ballistic vehicle can be regarded as constant in the range of velocity and altitude of interest, and gravitational effects can be ignored. The main conclusions which resulted from this break-through were that the maximum deceleration of a vehicle is independent of its mass, size, and shape and depends only upon the entry angle and velocity. For typical ballistic re-entry the heat transfer can be minimized by a blunt shape. Chapman [2] generalized the previous analyses.

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*Numbers in brackets refer to bibliography at the end of this report.

From his work it is possible to define the characteristics of the tra-
jectories of various types of vehicles and to determine the appropriate
environments [5]. Computations of trajectories have been made for a
wide variety of vehicles. Figure 1 is typical of the results of such
computations.

Heating rates incurred during ballistic re-entry are such that the
surface temperatures exceed the melting points of most metals. Without
some form of heat flow retardation the temperature inside the vehicle
will be too great for any payload to survive. Some form of heat shield
is an absolute necessity. The efficiency of a heat shield clearly de-
pends upon the amount of heat absorbed by the material and the amount
radiated away from the surface. These factors together determine the
amount of heat conducted to the structure and thus to the space within.

As pointed out by Roberts, Peters, and Hopko [4] of the Langley
Research Center, it is in the ability to absorb heat that the ablation
shield is superior to the heat sink. Keeping in mind the diagram of
Fig. 2, it is seen that in ablation a portion of the mass is vaporized
(this fraction will depend primarily on the viscosity of the liquid
produced by melting). In addition to the latent heat required to produce
this gas, a large amount of heat is absorbed during the convection of the
gas in the boundary layer so that it can be considered to be raised to
some temperature between the vaporization temperature and the external
temperature. It follows therefore that the heat capacity of the material
in gaseous form increases with the stagnation temperature of the stream
and therefore with the vehicle speed (whereas the capacity of a solid
heat sink is limited by the temperatures it can withstand).

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ALTITUDE ~ 10³ ft
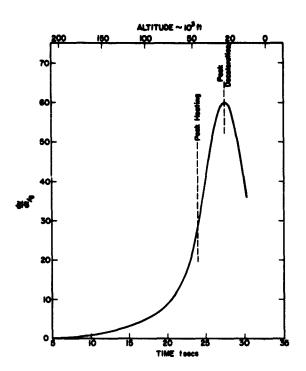
Fig. 1 Deceleration and heating for a typical ballistic re-entry.
Entry conditions: Alt 23000 ft
Vel 22000 ft/sec, $\theta = 22^{\circ}$ B = 2500

THE ABLATION PROCESS

INSULATION

ABLATION MATERIAL

HIGHLY VISCOUS LIQUID LAYER

GAS LAYER

$$\left. \begin{array}{c} \text{HEAT TRANSFER TO} \\ \text{SURFACE WITH} \\ \text{ABLATION SHIELD} \end{array} \right\} = \left\{ \begin{array}{l} \text{HEAT TRANSFER WITHOUT} \\ \text{ABLATION SHIELD} \\ \text{MINUS HEAT ABSORBED BY:} \end{array} \right.$$

A. SOLID SHIELD
B. LATENT HEAT OF MELTING
C. LIQUID FLOW
D. LATENT HEAT OF VAPORIZATION
E. GAS FLOW
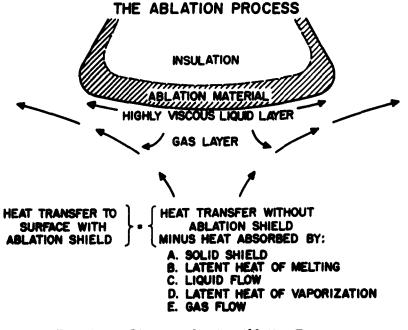
Fig. 2   Diagram showing Ablation Process

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The effective heat capacity of the ablation material is the amount of heat absorbed per unit mass lost (BTU/lb). Figure 3 shows a comparison of the effective heat capacities of teflon and quartz, two materials representative of distinct classes currently of interest in ablation studies. The ablation behavior of a body coated with such materials is very similar to that of a meteorite. Figure 4 gives an excellent resumé of such behavior. It is taken from Sin-I Cheng's paper on the mechanism of atmospheric ablation presented at the Ninth International Aeronautical Congress, Amsterdam, September 1958 [5]. In this paper Cheng illustrates that in the determination of the convective motion of a liquid layer, the action of effective gravity field primarily due to deceleration is equally important as the action of viscous shear of the gas motion. He concludes from his detailed study that the molten layer or liquid film on the surface of a decelerating body is always unstable irrespective of the large viscosity of the liquid or the molten mass, and of the relative wind blowing over the surface. The instability will develop into advanced stages, under sufficiently large decelerations, until droplets of the molten mass will be projected into the atmosphere. Thus interfacial instability under an effective gravitational field of appropriate magnitude will serve as an important mechanism in mass ablation.

Cheng's deduction with regard to the relationship between effective gravity and viscous shear force is amply verified in the outstanding work of Chapmann and his collaborators at the Ames Research Center [6]. Figure 5 shows, for purposes of comparison, photographs of an aerodynamically ablated glycerin glass sphere and a Tasmanian Tektite. The resemblance is striking. Chapman reports that the wind tunnel stream
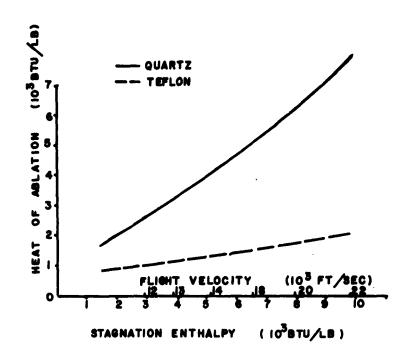
Fig. 3   Estimates of the heat of ablation for quartz and teflon. Subjected to turbulent heating.
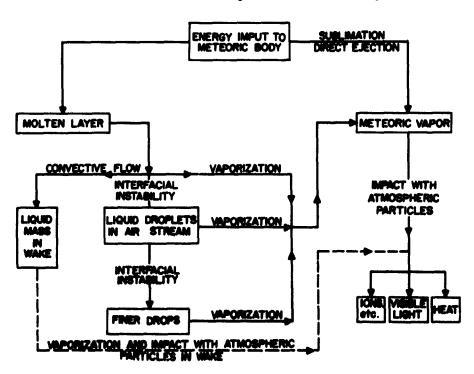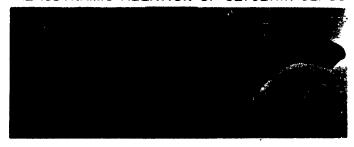
Fig. 4   Mechanisms of meteoric ablation. Courtesy Sin-I Cheng

AERODYNAMIC ABLATION OF GLYCERIN GLASS

TASMANIAN TEKTITE

Fig. 5   Comparison of Tasmanian tektite and ablating glycerin glass sphere
Courtesy NASA

Fig. 6   Ablated Aluminum Hemisphere showing effects of gravity on material loss.
Courtesy Polytechnic Institute of Brooklyn

was directed vertically upward. He remarks that it is significant that such an uncommon configuration could by obtained in the experiments only by adjusting very carefully the test conditions so that the aerodynamic force tending to push the ablated melt flow upward just balanced the gravitational force tending to pull it downward. In this experiment the gravitational body force in the vertical wind tunnel provides a dynamically similar analogue to the deceleration body force in re-entry flight. Both forces are directly parallel to the axis of symmetry and are exerted uniformly over each volume element. The fact that the grav- itational force in the wind tunnel is smaller than the corresponding deceleration force in flight is precisely compensated by proportionally smaller aerodynamic forces, so mechanical similarity is achieved between laboratory and flight conditions.

Cheng's general conclusion with regard to the instability of the molten layer is confirmed by the work of Anliker and Beam [7]. In their paper on the stability of liquid layers spread over simple curved bodies they emphasize the significance of interfacial instability in ablation by reference to an effect observed by Nardo, Erickson, and Kempner [8] in the Brooklyn hypersonic tunnel. This effect is shown in Fig. 6. In this photograph a pronounced difference between the ablation on the upper and lower surfaces of the model is observed. This asymmetry in ablation can be attributed to the fact that in the presence of gravita- tional body forces a liquid layer on the lower half of the hemisphere is unstable whereas on the upper half of the hemisphere a liquid layer assumes a stable equilibrium configuration.
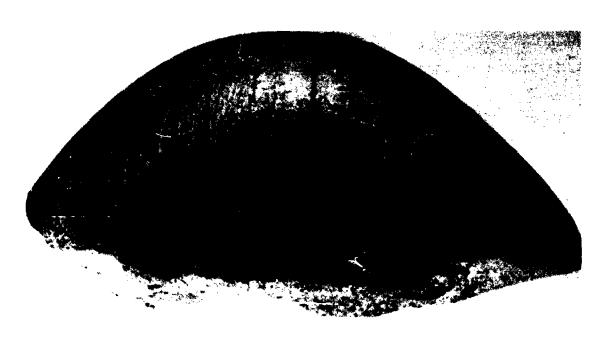
Fig. 7   Photograph of a stone meteorite showing lines developed by interfacial instability
Courtesy Purdue University

Feldman [2] in a paper on the instability theory of the melted surface of an ablating body when entering the atmosphere postulates a mechanism due to deceleration which would cause the formation of longitudinal grooves on the surface of an axially symmetric blunt body. He illustrates his contention by photographs of some stone meteorites which successfully entered the atmosphere. These are reproduced in Fig. 7.

The strong evidence of theory and corroborating data from meteoritic sources and wind tunnel tests leads us to the firm conclusion that inertia effects due to deceleration, rotation or allied causes must play a most important part in the ablation behavior of glass-like materials. It seems to us therefore that it should be included in ground simulation tests if we are to develop a rational family of ablation materials. However, so far as we are aware, no presently existing facility has this capability. As we shall show in subsequent portions of this paper, the inclusion of such effects is engineeringly feasible.

III. FEASIBILITY OF COMBINED AERODYNAMIC AND INERTIA SIMULATION

Complete simulation of missile or satellite re-entry conditions requires duplication of stagnation enthalpy, Mach number, pressure altitude, heating rate and gravitational effects. The development of a laboratory facility in which these effects can be completely simulated is an extremely difficult task. Therefore it must be recognized from the onset that the proposed facility, like all research tools, will have specific limitations with regard to the degree of simulation achievable.

It was shown in Ref. 1 that the maximum deceleration of a vehicle during re-entry is dependent upon the entry angle and velocity. It seems likely from the probable angles and velocities that a deceleration level of greater than 100g will not be met in any realistic system. In the case of the typical ballistic vehicle shown in Fig. 2 the maximum deceleration is 60g, occurring 27 seconds after re-entry. The maximum rate of change of deceleration is approximately 5g/sec. This deceleration is in a direction parallel to the line of flight.

It is apparent from the magnitude of the deceleration and the time through which it is sustained that motion of the vehicle relative to the gas stream can only be achieved in the true flight path. Thus it is essential to consider a hypervelocity tunnel and model together subjected to the desired acceleration profile. Such an arrangement will have a negligible effect on the flow. Linear motion of the system does not seem desirable due to the scale involved. Circular motion on a centrifuge appears quite attractive, since high centrifugal forces can be achieved with relatively low rotational speeds. A comparison of

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linear and circular motion is shown in Fig. 8. We propose therefore to investigate the practicability of a hypervelocity wind tunnel mounted on a centrifuge as a device for combined aerodynamic and inertia simulation.

The centrifuge has, in recent years, become a commonplace device in space environment simulation facilities. Consequently, many large machines have been built. Generally speaking, these machines are used to produce high accelerations rather than high rates of change of acceleration. Thus, since the time to constant angular speed is not of prime importance the power requirements are usually quite small, windage loss being the predominant factor in the establishment of the power needed. Because of the relatively high inertia of the rotor arm, control of steady angular velocity is not complex and can, in most facilities, be achieved with a simple manual system. A system of this "classic" type is quite suitable for the proposed facility so long as the effects of constant inertia loading are the only ones which we wish to simulate in our investigations.

It seems clear, however, that it might well be very desirable to attempt a more realistic inertia simulation and if this is the case the centrifuge will be of a somewhat different character than that which is currently accepted. No longer will the power be fixed by windage loss but instead will result from the very heavy forces required to accelerate or decelerate the centrifuge. We estimate that a centrifuge arm and tunnel complex of the type necessary for this work would have a minimum rotating mass of 10,000 lbs and a radius of gyration of the order of 12 ft. If we are to achieve an inertia loading on the specimen which corresponds to a rate of change of acceleration of 5g/sec in its flight direction, we should require a motor of approximately 1,000 hp

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	FINAL VELOCITY	DISTANCE REQ.	MAX. VELOCITY RELATIVE TO TRACK
LINEAR MOTION (ROCKET SLED)	20,500 FT/SEC	110,000 FT	20,500 FT/SEC
CIRCULAR MOTION (CENTRIFUGE)	110 RPM	18 FT RADIUS	207 FT/SEC

Fig. 8   Comparison of linear and circular motion of a wind tunnel for achieving 5 g/sec for 16 sec

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to bring the centrifuge up to operating speed. A similar magnitude braking effect would also be necessary.
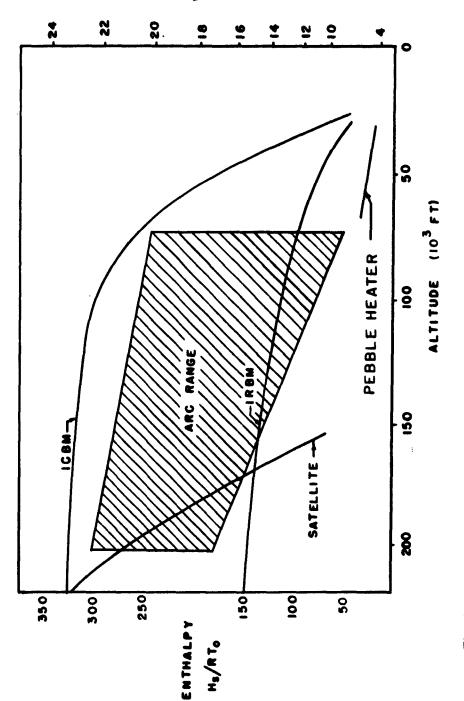
To provide power of this magnitude is expensive and probably not justified when we consider the duration of the test. A more logical approach would appear to be to use an inertia disk system. The adoption of a system of this kind would reduce the instantaneous power demand from approximately 1000 hp to approximately 150 hp. This would naturally mean considerable savings, not only in the motor costs, but also in transformers, switching gear and wiring. Of course, it would add some complexity insofar as some form of clutching mechanism would be essential to couple the inertia disk to the centrifuge proper and likewise to couple the centrifuge to an inertia brake. Such a system would clearly involve considerable engineering but it does not appear to be of such complexity that the engineering cost would exceed the saving of capital cost. Whichever type of system is adopted, a test section radius of 18ft appears to be realistic. With this radius the variation in g from nose to tail on a 6-in. long model is not more than 3 per cent and a loading of 80g can be achieved with 110 rpm. Such performance is clearly adequate.

A constant angular velocity system induces a purely radial inertia force on the test specimen. However, in a facility which attempts to achieve a variation in inertia loading, the angular acceleration of the centrifuge produces a tangential acceleration at the test section. For proper re-entry acceleration a component perpendicular to the flow is undesirable. This component can be eliminated by pivoting the wind tunnel on the centrifuge in such a manner the resultant acceleration is always parallel to the flow direction.

Enthalpy is of great importance in the testing of glassy type materials since the fraction of the material which is vaporized and the beneficial effects of gas injection are dependent upon it. Therefore, for ablation studies duplication of the correct enthalpy in the test gas for an appropriate time is essential. The variation of enthalpy with altitude and velocity for typical re-entry vehicles is shown in Fig. 9. Included also in this plot is the enthalpy simulation envelope achievable with an arc-heated facility of the present generation together with the capability range for pebble bed heater type tunnels.

It is generally accepted that the arc driven hypervelocity tunnel has the greatest simulation potential with respect to enthalpy and is therefore most suited to ablation studies. Therefore, we propose that such a tunnel be used in this complex. It is fortuitous that the adoption of a plasma system leads to considerable design simplification. The problems of ducting large quantities of air at extreme temperatures from some external generator are without doubt more complex than the dual problem of ducting low temperature air and feeding high voltage, high current power to a plasma generator on a rotating system. Seals suitable for transmission of large quantities of high pressure air through a rotating joint have already been developed for use in various centrifuge facilities [10], while the power transmission problem is of not greater magnitude than that experienced in large electrical rotating machinery.

Experience in classical ablation testing has shown that a two-inch diameter model is satisfactory for hypersonic ablation studies. A model of this diameter requires a test section diameter of the order of six inches. Of course shrouded test techniques can be used for larger models

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Fig. 9   Proposed arc operating envelope in relation to representative re-entry trajectories

if desired. Hence, it is accepted in this paper that a six-inch nozzle exit diameter will be adopted. Plasma units capable of driving such a tunnel have already been built and successfully operated by a number of organizations, for example the AVCO Corporation and the General Electric Company. A study of typical existing facilities shows that the probable mass and size of a suitable generator is such that from inertia and space aspects no undue difficulty would be experienced in a centrifuge application. Experiments with a prototype electric arc have shown that a design compatible with the anticipated inertia loading is feasible. Hot ducts, such as tail cones on jet engines, have demonstrated that the necessary ducting for the tunnel is a design question largely resolved. In a like manner fuel and hydraulic lines in operational aircraft experience comparable inertia loadings to those which will be met by the service facilities. Therefore the design of an adequate plasma tunnel compatible with a practical centrifuge appears feasible.

The need to simulate altitude makes a large vacuum system essential. This system will require up to 200 microns to be drawn in order to simulate an altitude of 200,000 feet. Vacuum equipment and sealing techniques in current use are adequate for such an achievement [11]. Installation of the centrifuge within the vacuum sphere would unquestionably be a space saver and a very good safety measure. It will also considerably enhance the capability of the facility with regard to adaption to other environmental testing, and to low density aerodynamic research.

The miscellanea of additional mechanical detail which is clearly required for such a facility is of precisely the same character and

scope as would be required for a comparable static plasma system. Thus no engineering development problem is posed here.

It is concluded therefore that the design and development of a hypersonic wind tunnel carried on a centrifuge is well within the present state of the art for all components. Essentially it will result in the combination of proven techniques.

IV. ENGINEERING EQUIPMENT SPECIFICIATION

A block diagram of the proposed facilitiy is given in Fig. 10. This diagram shows the essential components of the facility. The engineering detail of these are as follows.

4.1. HYPERSONIC TUNNEL

The proposed tunnel capability is:

1. Maximum enthalpy: $300\ h_s/RT_0$
2. Maximum stagnation pressure: 50 atmospheres
3. Simulation altitude: 70,000 - 200,000 feet
4. Mach number: 3 - 7

4.1.1. Electric Arc.

An arc operating envelope in relation to several typical trajectories was shown in Fig. 9. Performance as outlined there has been obtain in existing facilities [12]. It should not be considered either a maximum attainable or even desired, but is merely the presently achieved. Further development in the design of electric arc units will permit higher operating levels and this development is certainly to be expected [13].

Experience with large air-arc-tunnels at AVCO and General Electric shows that an overall efficiency of the order of 50 per cent is the best that can be expected for the size and operating range specificed. AVCO, primarily through the work of Brogan [14], has shown that the energy loss, and therefore the overall power requirement, can be minimized by adopting a configuration in which several smaller arc units discharge into a common plenum. The resulting design resembles

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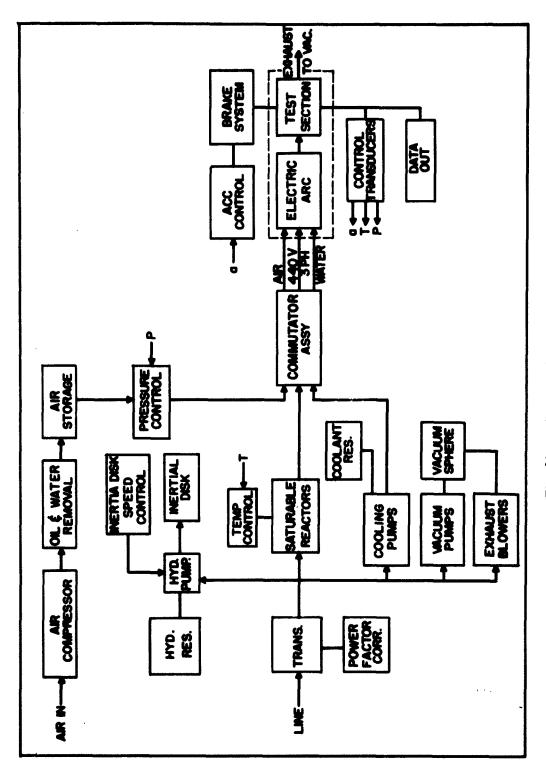
Fig. 10   System Flow Diagram

a radial engine.   This system uses smaller arc units which by virtue
of their size are simpler to construct and operate. In addition the
added flexibility of partial operation is available for lower enthalpy
conditions.

It is desirable to utilize an AC arc system rather than a DC system
since AC is more efficient at high power levels [15]. The power dissi-
pated in the ballast resistance needed for DC arc operation becomes pro-
hibitive at high operating levels. Furthermore, large AC power supplies
are more readily available. A pilot model of an AC arc of the type pro-
posed is under development at Stanford University. Figure 11 shows a
cross-sectional view of this type with two units per phase of a three
phase power supply. Figure 12 shows the arrangement of these units and
their common plenum chamber.

The power required to produce the necessary enthalpy in the gas
stream depends upon the mass flow of the system and the arc efficiency.
For plenum pressures of 50 atmospheres, as specified for this facility,
the power input to the gas will be 4-7 megawatts. To obtain this level
with present arc efficiencies will require 7-12 megawatts to the system.

Dissipation of the arc losses is to be provided by high pressure
water cooling. The major areas to be cooled are the anode, cathode, and
plenum walls. The use of a cooled copper anode and cathode instead of
carbon will reduce the flow contamination to approximately 0.2 per cent,
however, exposure of these elements to the radiation from the arc at a
pressure of 50 atmospheres results in a severe cooling load for the
system. AVCO has operated an arc facility in this range and shown that

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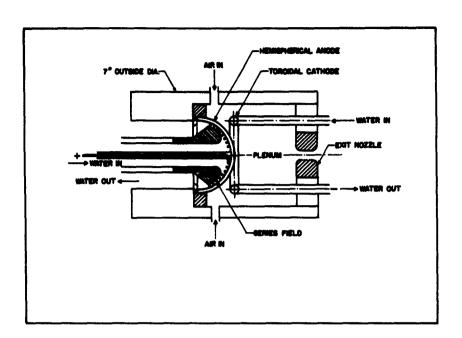
Fig. 11   Prototype A/C ARC Unit
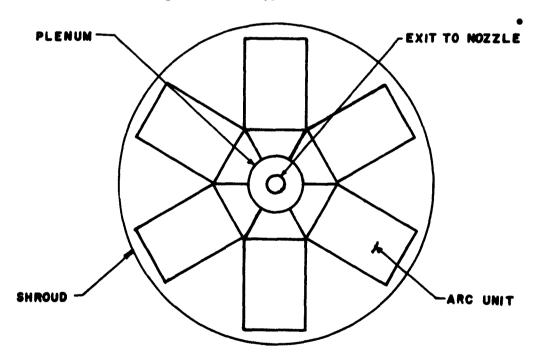
Fig. 12   Radial ARC Arrangement

cooling water requirements for the anode are 150 gallons per minute at 200 psi for a one-megawatt arc power in the gas.

4.1.2. Nozzle. The three design features desirable for the hypersonic nozzle are, (1) Minimum length for a given expansion ratio, (2) Suitable for operation at maximum enthalpy conditions for up to 200 seconds, and (3) simple to install and readily interchangeable with other nozzles of the same family.

Since the wind tunnel must be suitable for centrifuge installation a minimum length is desirable. An axisymmetric nozzle satisfies this condition very well. It has, at the same time, an advantage when testing models which are solids of revolution as is frequently the case with ablation specimens. It is recognized that a change in Mach number must be accompanied by a change in nozzle length even though the mass flow be maintained at a constant value. Thus the provision for variation in Mach number must call for simplicity in tunnel connections and flexibility in the mounting arrangements and positioning for the test section and diffuser.

Capability for long-time operation is primarily a problem of maintaining the throat temperature at a level which is low enough to prevent rapid burn-out. Experience in other facilities indicates that this is a most difficult engineering problem. A Mach 5 nozzle suitable for use in this installation is shown as Fig. 13. The nozzle is cooled by a water manifold and by cold air injected into the boundary layer at the throat. Designs of this type have been operated satisfactorily at stagnation pressures of 800 psi and stagnation temperatures of 5000 °R.

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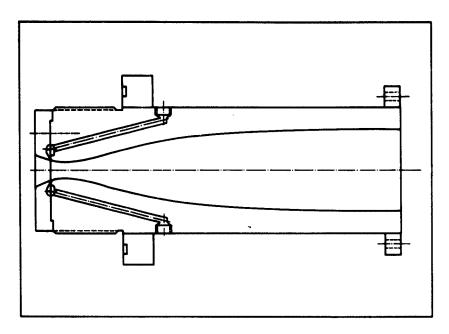
Fig. 13   Cross section of mach 5 nozzle showing injection cooling

TEST SECTION

PLENUM

ARC UNIT

HEAT EXCHANGER

EXHAUST

DIFFUSER

NOZZLE

SHROUD
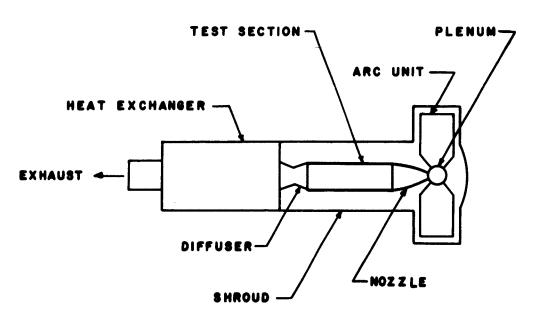
Fig. 14   Arrangement of wind tunnel components

4.1.3. Test Section.

The nozzle must be followed by a test section suitable for model mounting and observation and satisfactory for flow containment. This section, lying between the nozzle and the diffuser, will vary in character depending upon the tests to be made. Therefore, it must be interchangeable with all members of its family. Downstream of the test section a diffuser provides flow stability and partial pressure recovery. Cooling for the test section and diffuser will be accomplished by enclosing the components in a shroud through which the incoming air to the plasma generator is passed. Additional cooling for the model support and diffuser throat will be provided by a water system.

A diagram showing the relative location of the plasma generator, Mach 5 nozzle, test section and diffuser is presented in Fig. 14.

4.1.4. Heat Exchanger.

A heat exchanger will be provided immediately downstream of the diffuser. This will reduce the temperature of the exhaust gas prior to release into the vacuum system and increase the overall efficiency of the system by preheating the inlet air to the electric arc. It is recognized that the effectiveness of this heat exchanger will be limited due to the high velocity and low pressure of the flow. However, the reduction of the stagnation temperature to 2000°R will be satisfactory as will be shown in the vacuum system discussion.

4.2. CENTRIFUGE DESIGN

Detailed studies of an inertia disk drive for the centrifuge tunnel indicate that a disk and rail system as shown schematically in Fig. 15 is the most logical design. In such a system the tunnel and cage are suspended from the upper rail system and are in sliding contact with the

RAIL AND SLIPPER

GIMBAL ARRANGEMENT

FIXED STRUCTURE

WIND TUNNEL

TUNNEL CASE

VIEWING PORT

SERVICE
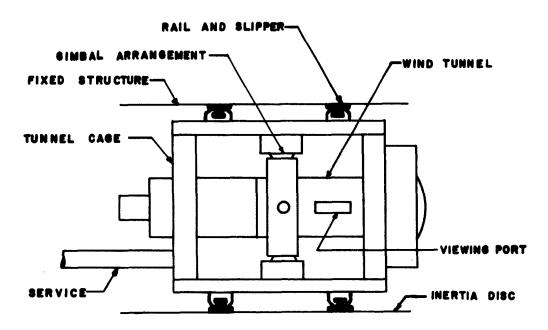
INERTIA DISC

Fig. 15   Wind tunnel carriage and track arrangement

lower rails while the disk is brought up to peak rotational velocity. No time limit need be imposed for this operation and therefore the power requirement will be small. When the inertia disk is at the appropriate RPM the cage is released from the suspension system and clutched to the rails on the disk in such a manner that it is brought up to disk rotational speed in accordance with the desired program.

It is estimated that the weight of tunnel and cage will be of the order of 2000 lbs. With this weight and a radius of 18 ft, a 150 HP drive motor could maintain the disc speed virtually constant when the tunnel and cage is clutched to the disk and accelerated at a rate of 5g/sec radially. Deceleration can be accomplished by the reverse process. The tunnel and cage are released from the lower rail system and clutched to the upper stationary rails.

The disk drive system proposed is similar to that adopted by the Rucker Company. The centrifuge is fitted with a large driving ring gear and hydraulic motors are geared to this at various positions around its periphery. These driving motors are fed by matching pumps. A centrifuge system of the type described fits conveniently into the base of the partial sphere desired for the vacuum tank.

It is considered that an out-of-balance of between 5 and 10 per cent is the maximum which would be desirable in the system. Therefore, since the use of a cage and rail system is to a large extent dependent for simple operation and control upon not using a counterbalance weight, the inertia of the disc will need to be of the order of 4×10^5 ft lbs $\sec^2$. This can be achieved with proper radial weight distribution by a disk weighing between 40,000 and 50,000 lbs.

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4.3. SERVICES

4.3.1. Electrical Supply. In paragraph 4.1, the tunnel was specified to have a maximum enthalpy of 300 h_s/RT_0, a Mach number range of 3 to 7, maximum stagnation pressure of 50 atmospheres and an altitude simulation range of 70,000 to 200,000 ft. The maximum power required to drive the arc is 12 megawatts. The cooling water pumps associated with the arc need an additional 375-500 kilowatts. Therefore, the maximum power requirement for the system is of the order of 12.5 megawatts. In this assessment of overall power, the power needed to drive the auxiliary services, such as compressors, vacuum pumps and vacuum tank scavenger system are not included since these units operate only when the main part of the facility is shut down. A considerable saving in expense of installation can be made by recognizing that the duty cycle for operation is approximately 200 sec peak load followed by at least 8 hours off-load. This limited duty cycle will permit the transformers to be operated at a considerable overload factor.

For the successful operation of the arc over a wide enthalpy range it is essential to provide regulation of the current to the arcs. For this purpose six current control units will be necessary, one for each chamber of the plasma generator. If these regulators have a range of 60 to 100 per cent of their maximum output, the power transferred to the gas stream can be made to vary between 0.6 and 6.0 megawatts. In the same way that cost reduction can be made in the transformer selection by use of the appropriate duty cycle so can savings be made in the current regulators by a similar consideration.

The transmission of this large amount of power from the fixed power supply to the rotating plasma system requires a substantial commutator on the rotor axis. Such commutators are common in very large electrical machines and are, therefore, no problem to electrical engineers.

4.3.2. Air Supply and Storage System. The intermittent nature of the facility makes it economically desirable to use a storage system. The specification outlined in paragraph 4.1, for an operational time of 200 seconds, requires 150 cu ft of air at an initial pressure of 3000 psi and a final pressure of 750 psi. For this a spherical pressure vessel of 79-1/4 inches inside diameter, 4-1/4 inches wall thickness will be used. The compressor proposed is of the Hardie-Tynes type. This is a 4-stage compressor driven by a 75 hp motor. It has a capacity of 30 cu ft of compressed air per hour at 3000 psi and, therefore, can inflate the sphere from 750 to 3000 psi in three hours. It will require approximately 40 gallons of cooling water per minute at a pressure of between 50 and 150 psi.

4.3.3. The Rotor Hydraulic Drive System (Fig. 16). A 150 hp motor is used to drive 2 positive displacement 3000 psi pumps. These pumps are similar to the hydraulic motors which are geared to the centrifuge. One of them is of the variable displacement type, thus affording a means for controlling power to the centrifuge. Other hydraulic components such as control valves involve very small flow and should not require additional pumps.
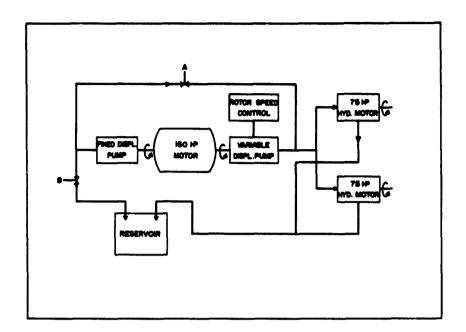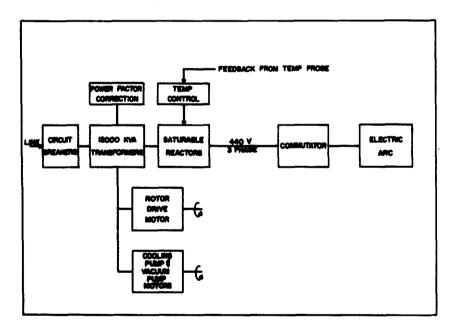
- 29 -

Fig. 16   Hydraulic System

Fig. 17   Electrical Power System

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4.3.4. **External Cooling System.** Approximately 1500 gals of cooling water at 250 psi must be provided during a 200 sec run to dissipate the 6MW power loss from the arc system. It is estimated that 375-500 hp is needed to drive the necessary pumps. Power for these pumps is available from the vacuum pump system if suitable clutching arrangements are made.

In addition, the air compressor and the vacuum pump system require 35 gals per min and 70 gal/min of cooling water during their periods of operation. These systems will not be used simultaneously for the arc and therefore the same reservoir can be used for both. For this latter operation, however, a small cooling tower and circulating pump is necessary. The proposed system is as shown in the block diagram of Fig. 17.

4.3.5. **Vacuum System.** The vacuum system will consist of a 64 ft diameter steel sphere and vacuum pumps for reducing the pressure to 200 microns. Such a pumping system is shown in Fig. 18. This cascade arrangement utilizes 2 stages of large volume Roots pumps and a final stage of the eccentric cam, oil seal type. Although the Roots type pumps are limited to an operating compression ratio of approximately 2, they are exceptional in their ability to handle large volume flow and thus reduce the size of pump required for the final stage. Utilizing a proceedure of operating stages 1 and 2 from atmosphere to 4000 microns and then stages 1, 2, and 3 for final pump-down to 200 microns will minimize the motor size required for the first stage pump. The time for pump-down using such a proceedure will be 9.5 hours.

During operation of the hypersonic wind tunnel the maximum influx into the vacuum system will be 7 pounds per second at 2000° R. This
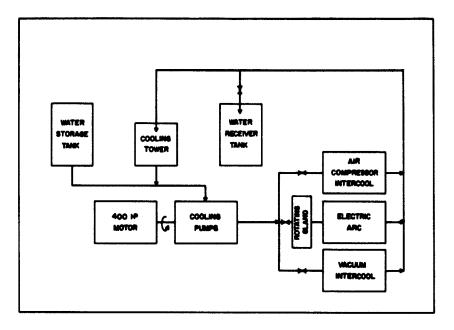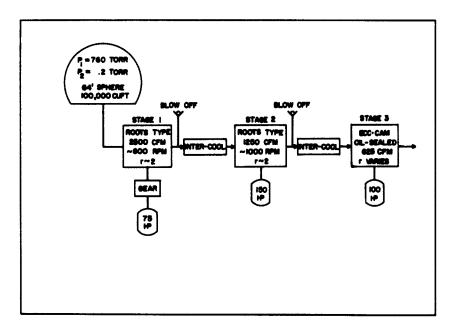
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Fig. 18   Cooling System

Fig. 19   Vacuum System

influx will raise the pressure in the sphere to atmospheric in approx-
imately 250 seconds. Such a pressure variation is compatible with the
altitude simulation for re-entry which the test facility is intended to
produce. The resultant temperature in the sphere will approximate
closely that of the input gas since the mass included at 200 microns is
negligible compared to that of the final conditions. This relatively
high temperature will not be critical for the structure. It can be
shown that if the shell thickness is taken as only 1/2 inch and all of
the gas energy is absorbed by the shell the resultant structural temper-
ature will be 215°F. Absorption of the gas energy by the shell is to
be minimized by purging the shell with cold air at the completion of a
test. Furthermore, cooling of the shell during blow-down of the tunnel
by an external water spray can be easily accomplished.

4.4. CONTROL SYSTEM REQUIREMENTS.

The simulation of re-entry conditions in the facility will require
control systems for gas flow and inertial loading which can be made to
follow a specified program. Since operation will be limited to a fixed
nozzle configuration for any specific test the flow conditions will be
determined by the stagnation temperature and pressure. A pressure con-
trol system has been built and operated successfully in the required
range of 0 to 50 atmospheres for the pebble bed heated hypersonic wind
tunnel at Stanford University. This system is described in Ref. 16.
Such a system, with slight modification, should be adequate for con-
trolling the arc plenum pressure in the proposed facility. The assump-
tion that the arc plenum pressure represents the stagnation pressure of
the flow is consistent with practice in other arc installations.

Since the electric arc is basically a constant voltage device the stagnation temperature is to be controlled by current regulation. The proposed power regulation of 60 to 100 per cent should not present a major problem as current regulators of this size and operating range are readily procurable. A difficulty associated with temperature control will be in the measurement of stagnation temperature. Continuous measurement of temperatures of the magnitude proposed (6000°F) is extremely difficult to obtain with total temperature probes. Thus it may be necessary to resort to a sampling probe technique or possibly an optical temperature measurement system.

The problem of controlling to a steady acceleration condition is one of maintaining a constant angular speed of the inertia disk. This is easily accomplished with the proposed hydraulic drive by a simple contactor control system or even manually. Reproduction of a prescribed acceleration trajectory is somewhat more complex. The cage containing the wind tunnel must be accelerated at the required rate by clutching to the inertia disk. Furthermore, the wind tunnel will have to be pivoted within the cage in such a manner that its position can be servo adjusted until the acceleration vector on the model lies in the flow direction and follows the prescribed program. The above described motion require three coordinated control systems, one for the motion on the disk of the cage and two for the positioning of the tunnel within the cage. Accelerometers will be used as the feedback devices, two perpendicular to the axis of the tunnel and one along it. The control systems are shown schematically in Fig. 20.
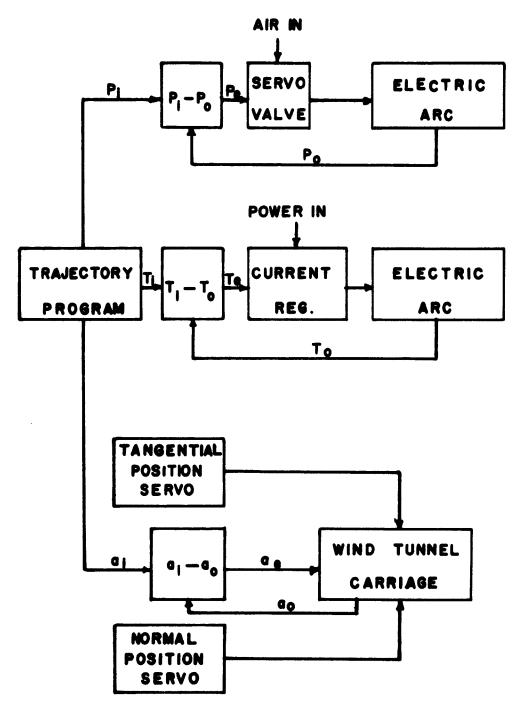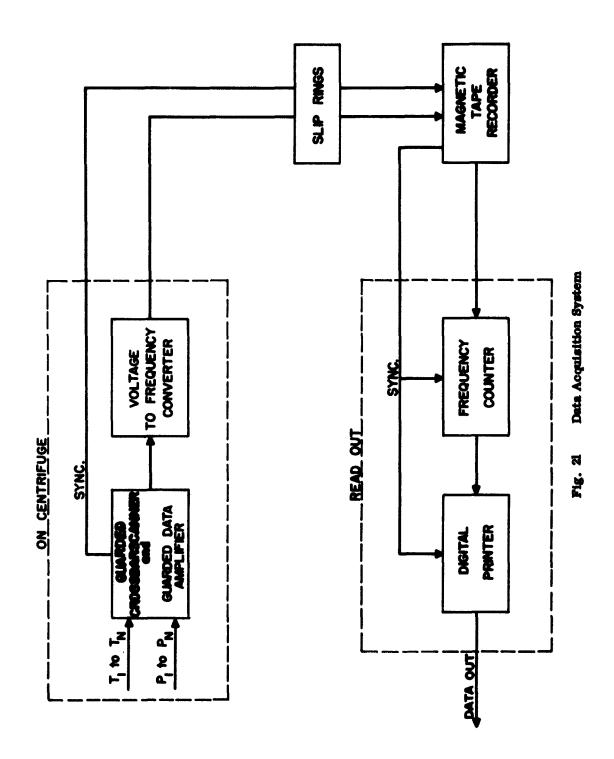
Fig. 20   Diagram for combined pressure, temperature and acceleration control systems

4.5. DATA ACQUISITION

Measurement of the pressures, temperatures and their distribution over the model is essential in ablation testing. The ability to measure these quantities, transmit and record them for subsequent analysis, will thus be a prime requirement for the facility.

The feasibility of utilizing a sampled data system for measurement can be established from observation of the variation with time of the pressures and temperatures on an ablating body. Incorporating such a technique reduces the equipment which must be installed on the centrifuge and which must therefore be designed for high g, high temperature operation. A time sharing system suitable for this type of installation is shown in Fig. 21. It uses a mechanical switch system with a commutation rate of 40 to 50 channels per second. Voltage-to-frequency conversion prior to the slip rings obviates the problem of noise associated with commutation of low voltage signals. Furthermore, the frequency signal is compatible with magnetic tape recording. The playback of the tape at a low speed will permit the use of low speed frequency counter and printer units for subsequent data reduction.

Visual observation of the model has proven valuable in the analysis of ablation tests results. Thus it is desirable to incorporate a closed circuit television system. An additional need for high speed photography will require the installation of photography equipment on the centrifuge since the scanning rate of television systems is limited. These two systems will provide both real time observation and a high speed record of the ablation tests.

SLIP RINGS

MAGNETIC TAPE RECORDER

ON CENTRIFUGE

VOLTAGE TO FREQUENCY CONVERTER

GUARDED CROSSBAR/CARRIER and GUARDED DATA AMPLIFIER

SYNC.

T_1 to T_N

P_1 to P_N

READ OUT

SYNC.

FREQUENCY COUNTER

DIGITAL PRINTER

DATA OUT

Fig. 21   Data Acquisition System

V. SUMMARY AND CONCLUSIONS

This paper draws attention to the significant effect of inertial loads experienced during re-entry on the process of ablation. It examines the feasibility of creating a ground-test facility in which re-entry deceleration can be simulated in a high velocity, high enthalpy gas flow. The conclusion is reached that a centrifuge mounted, electric arc heated, hypersonic tunnel can be developed with the necessary capability for studies over a wide range of re-entry trajectories. The essentials of such a design are presented.

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